A Simulation Evaluation of a Human Centered Approach to Flight Deck Procedures and Automation for En Route Maneuvering

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Background

- Distributed Air Ground Traffic Management (DAG-TM) is a proposed solution for expanding airspace capacity limits.
- In June 2004, research teams at the National Aeronautics and Space Administration (NASA) Langley Research Center and Ames Research Center conducted a joint human-in-the-loop experiment investigating the feasibility and operational benefits of one concept element (CE) under consideration as part of the DAG-TM program: *CE 5 En Route Free Maneuvering*.

En Route Free Maneuvering

The intent of the DAG-TM En Route Free Maneuvering concept element is to improve airspace capacity by allocating separation responsibilities to appropriately equipped “autonomous” aircraft. These aircraft fly according to *Autonomous Flight Rules (AFR).*

Goals of The En Route Free Maneuvering Study

Evaluate whether autonomous operations in a *mixed* en route and transition airspace are *feasible* and *scalable*

- **Mixed** – Both managed aircraft flying according to instrument flight rules (IFR) and autonomous aircraft (AFR) share the same airspace
- **Feasible** – Accommodates basic procedural, workload, and safety considerations
- **Scalable** – The number of en route aircraft can be significantly increased beyond present day limits

Mixed Operations

- Both IFR and AFR aircraft share en route airspace
- ATSPs manage IFR aircraft in a manner similar to today's operations, and maintain IFR-IFR separation.
- AFR aircraft equipped with on-board CDTI and CD&R maintain separation from other AFR and IFR aircraft.

Approach

- Joint Ames-Langley simulation with simulated flight decks at both centers and simulated ATC at Ames.
- The airspace was a modified portion of the airspace in and around ZFW and Dallas/Fort Worth TRACON.

Task

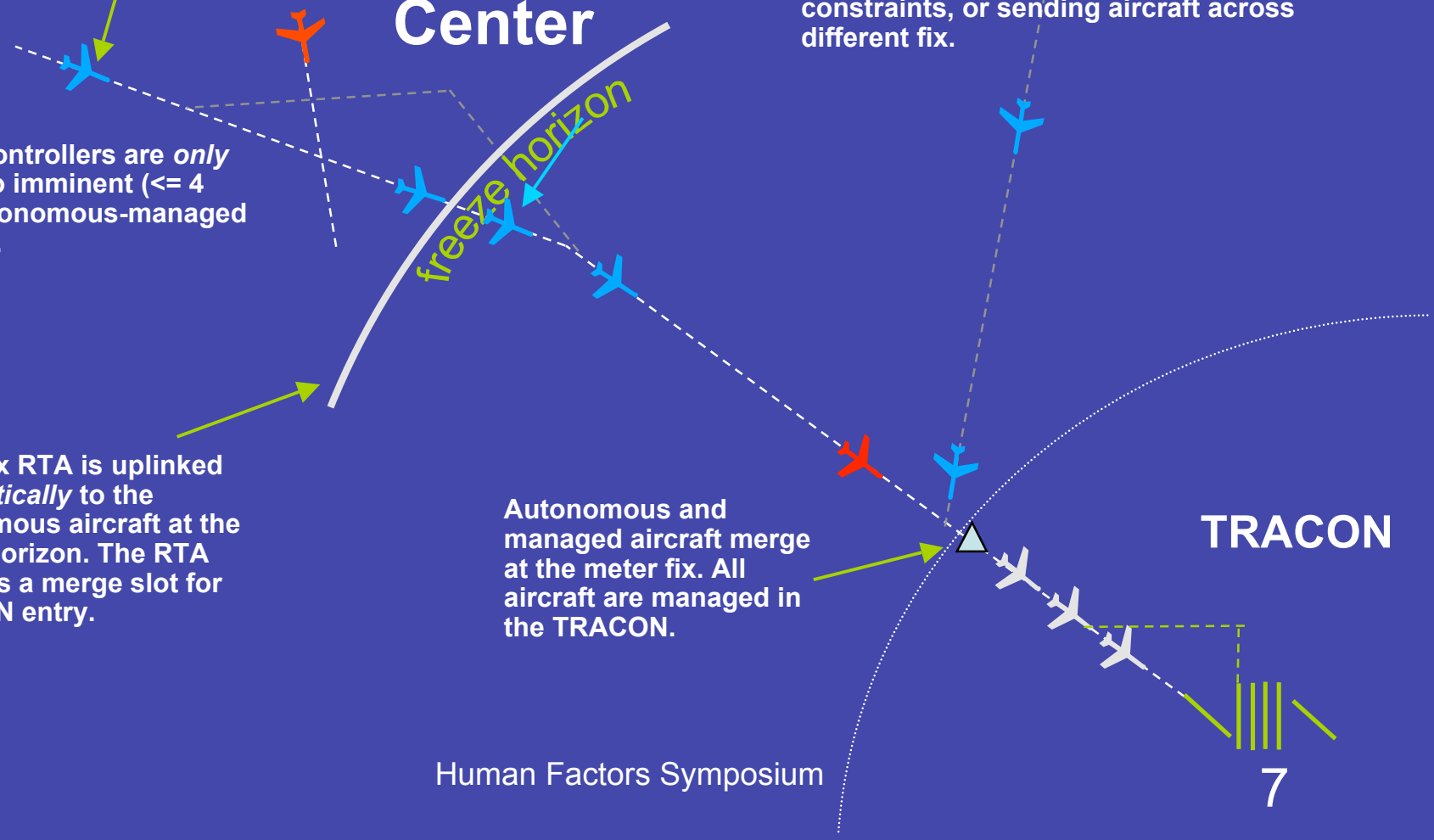
Autonomous aircraft are responsible for solving *all* conflicts.

Center controllers are *only* alerted to imminent (<= 4 min.) autonomous-managed conflicts.

Meter fix RTA is uplinked *automatically* to the autonomous aircraft at the freeze horizon. The RTA provides a merge slot for TRACON entry.

If an autonomous aircraft cannot meet RTA, flight crew must alert controller ASAP. Workload permitting, the controller will accommodate by assigning new RTA, relaxing meter fix altitude or speed constraints, or sending aircraft across different fix.

Autonomous and managed aircraft merge at the meter fix. All aircraft are managed in the TRACON.



Autonomous Flight Rules (1)

Pilots of AFR aircraft

- May choose their own route and altitude.
- Must ensure separation of ownship from all other aircraft (5 NM lateral, 1000 ft vertical).
- Must give way to managed (IFR) aircraft.
- When burdened, must resolve predicted conflicts prior to 2 minutes to loss of separation (LOS).
- Must not create near-term conflicts (< 4 minutes) with any aircraft when maneuvering or changing flight modes.

Autonomous Flight Rules (2)

- Must conform to arrival clearance at entry to TRACON.
- Must meet traffic flow management constraints (e.g, required times of arrival - RTAs) assigned by an Air Traffic Service Provider (ATSP).
- Must notify ATSP if arrival clearance constraints cannot be met and request an amended clearance.

ATSP Responsibilities

- Ensure separation between all managed (IFR) aircraft, resolving all predicted IFR-IFR conflicts.
- Not create near-term (< 4 minute) conflicts with AFR aircraft when maneuvering IFR aircraft.
- Provide metered arrival slots based on airspace, airfield, traffic density, and other constraints, and make those slots available to all aircraft (IFR and AFR) on a first-come, first-served basis.
- When contacted by off-schedule AFR aircraft, reintegrate them into the arrival sequence, but only as traffic permits.

Research Hypotheses

- Mixed operations in high-traffic density sectors are safe and do not degrade throughput and efficiency compared to operations with all managed aircraft.
- The number of total aircraft in a sector can safely be increased (beyond ATSP manageable levels) if the number of managed aircraft remains at or below current-day high-density levels.

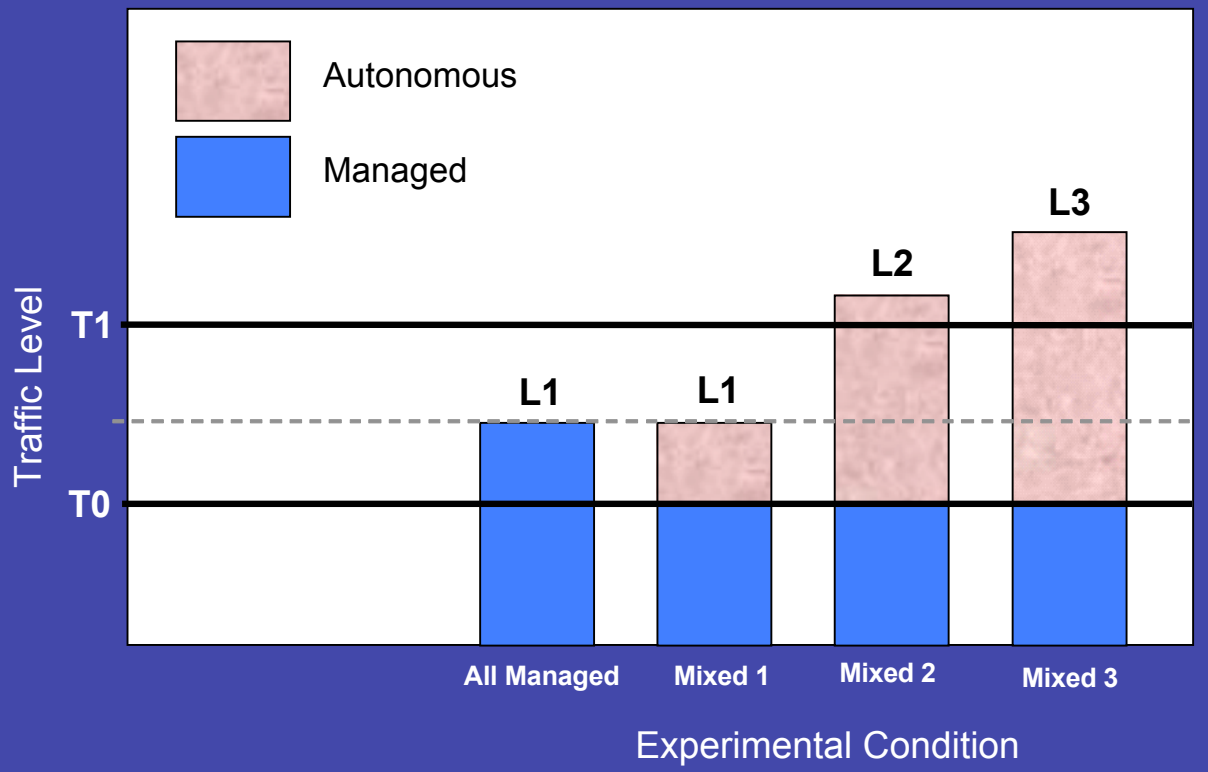
Experimental Design

3 Traffic Levels:

- **L1:** High Managed
- **L2:** Intermediate
- **L3:** High

4 Conditions:

- L1 traffic, all managed
- L1 traffic, mixed operations
- L2 traffic, mixed operations
- L3 traffic, mixed operations



T0: Threshold approximating current day monitor alert parameter.

T1: Threshold above which managed-only operations may become unmanageable.

Traffic counts to achieve these levels were established in simulation.

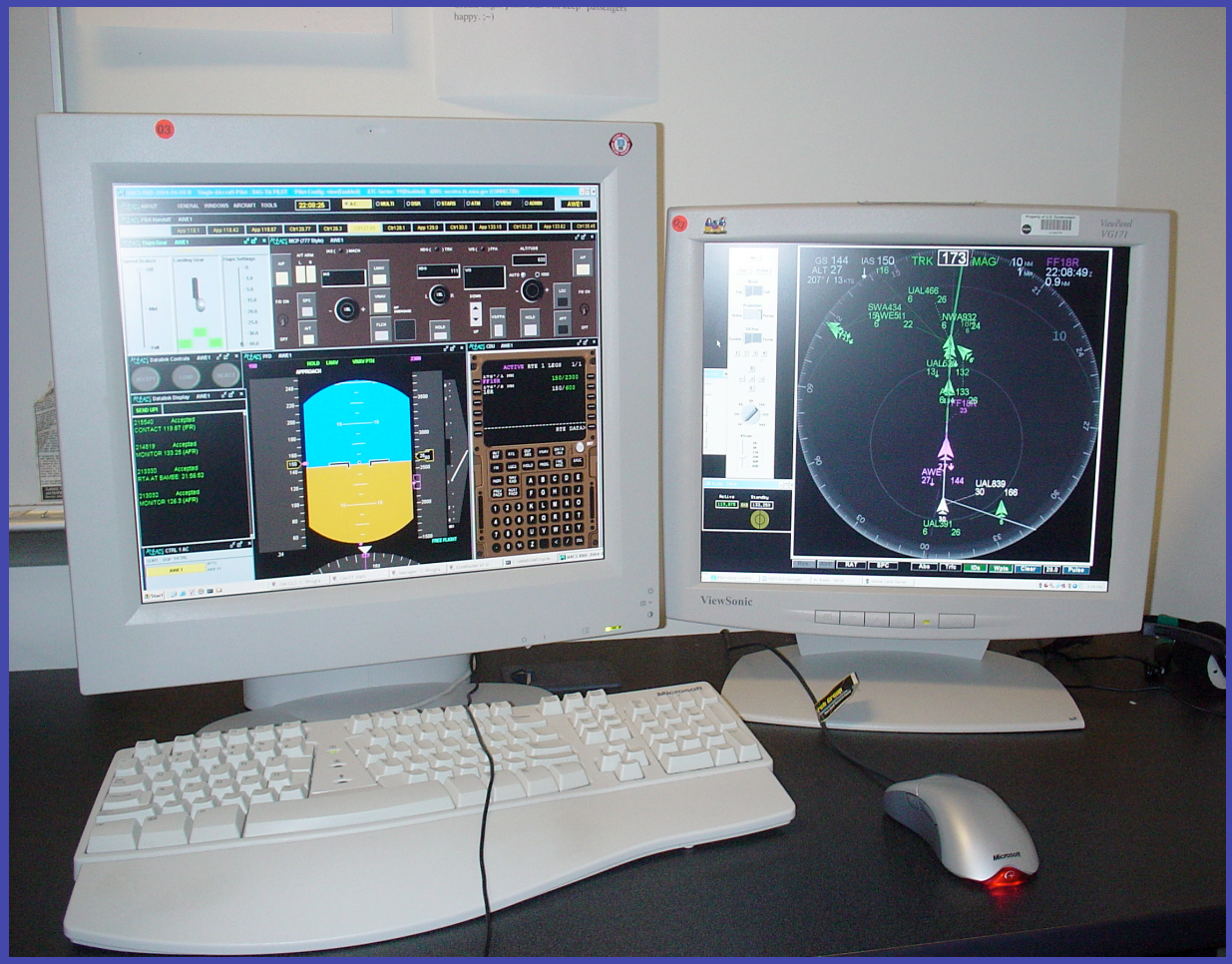
Ames Participants

- Ten air transport rated pilots - all had previous experience with the DAG-TM project, having participated in several previous studies. The mean number of flight hours for each pilot was 11,000 hours, with a mean of 4,00 hours of glass cockpit experience.
- Five certified FPL air traffic controllers - all had previous experience with the DAG-TM project, having participated in several previous studies.

Pilot Assignments

- Eight subject pilots flew eight single pilot desktop simulators.
- Two pilots flew the full mission flight simulator, functioning as a two-pilot crew.

CDTI Single Pilot Station



Advanced Concept Flight Simulator (ACFS)

The ACFS is a 6-degree-of-freedom full mission flight simulator equipped with

- Future Air Navigation System (FANS)-type datalink capabilities.
- 3D-CDTI at both the captain's and the first officer's position.

Pseudo-Pilot Stations

3D Cockpit Display of Traffic Information

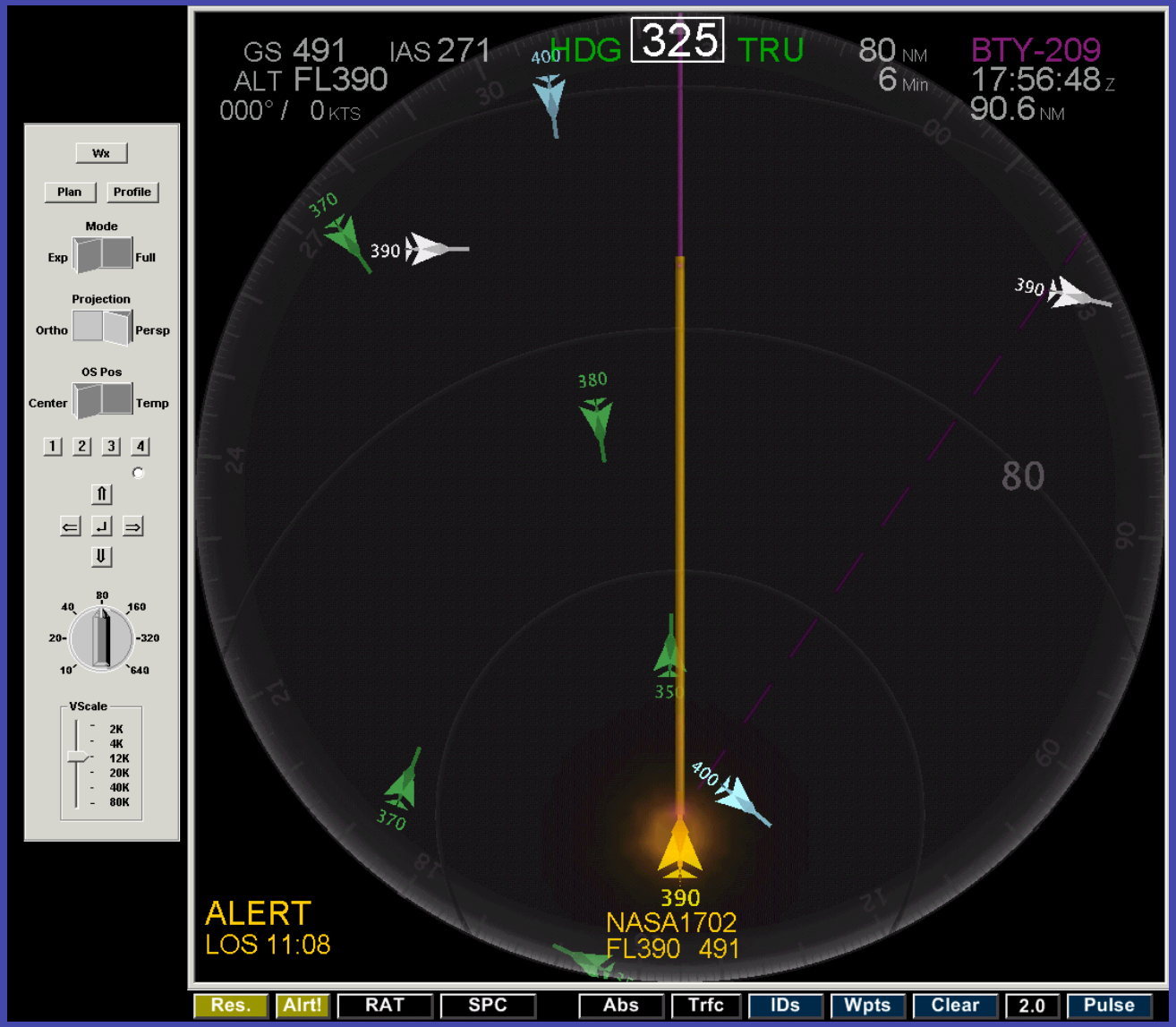
- The 3D-CDTI is a Decision Support Tool (DST) with specialized features that support free maneuvering:
  - Display of traffic with current flight status and flight plan data
  - Strategic conflict detection and alerting
  - Automated conflict resolution advisories
  - Graphic flight planning
  - RTA management
  - In-trail spacing

CDTI Display Functionality

- The traffic display provides pilots with aircraft state information and 4D intent information.
- An aircraft's position can be viewed over time by displaying a pulse that moves along the planned flight path relative to its broadcasted speed.
- Pilots can also display traffic in a 3D view using various display orientations with respect to ownship.
- Pilots may design and execute new flight plans which resolve conflicts while not creating new conflicts
- Pilots may use MCP operations to plan off-flight plan operations to resolve conflicts

CDTI 3D Display

Conflict Resolution Using Altitude



CDTI 3D Display

- Conflict Resolution Using Lateral Change

Simulation Results

Performance

Post Simulation Questionnaire

Workload Rating

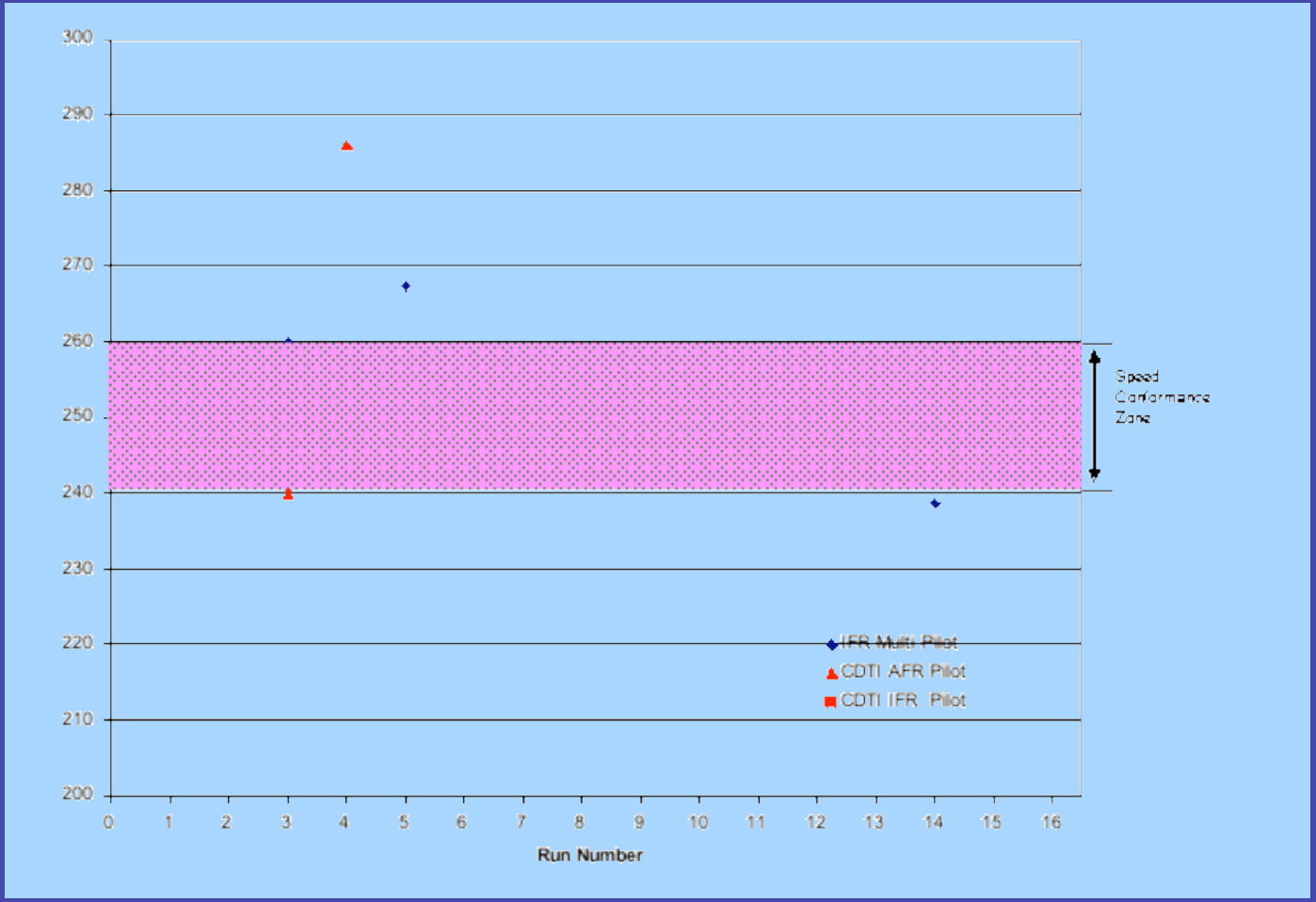
Observer Notes

Separation Violations by Conflict Type and Condition

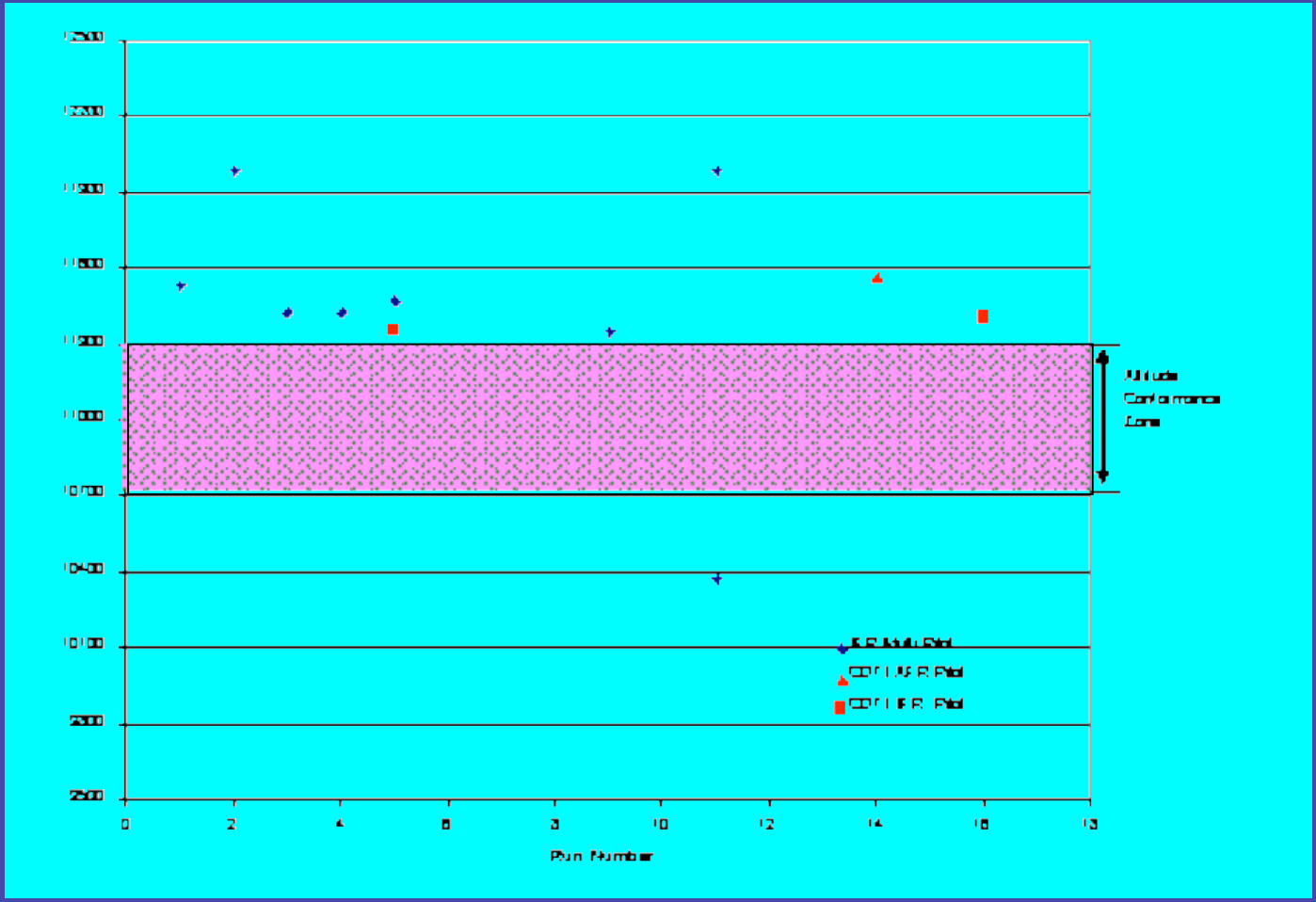
Conflict Type	All Managed	Mixed 3	Mixed 3	Mixed 4	Total
IFR-IFR	2	2	1	2	7
IFR-AFR	-	0	0	4*	4
AFR-AFR	-	0	1*	1*	2
Total	2	2	2	7	13

* Multi-pilot stations only

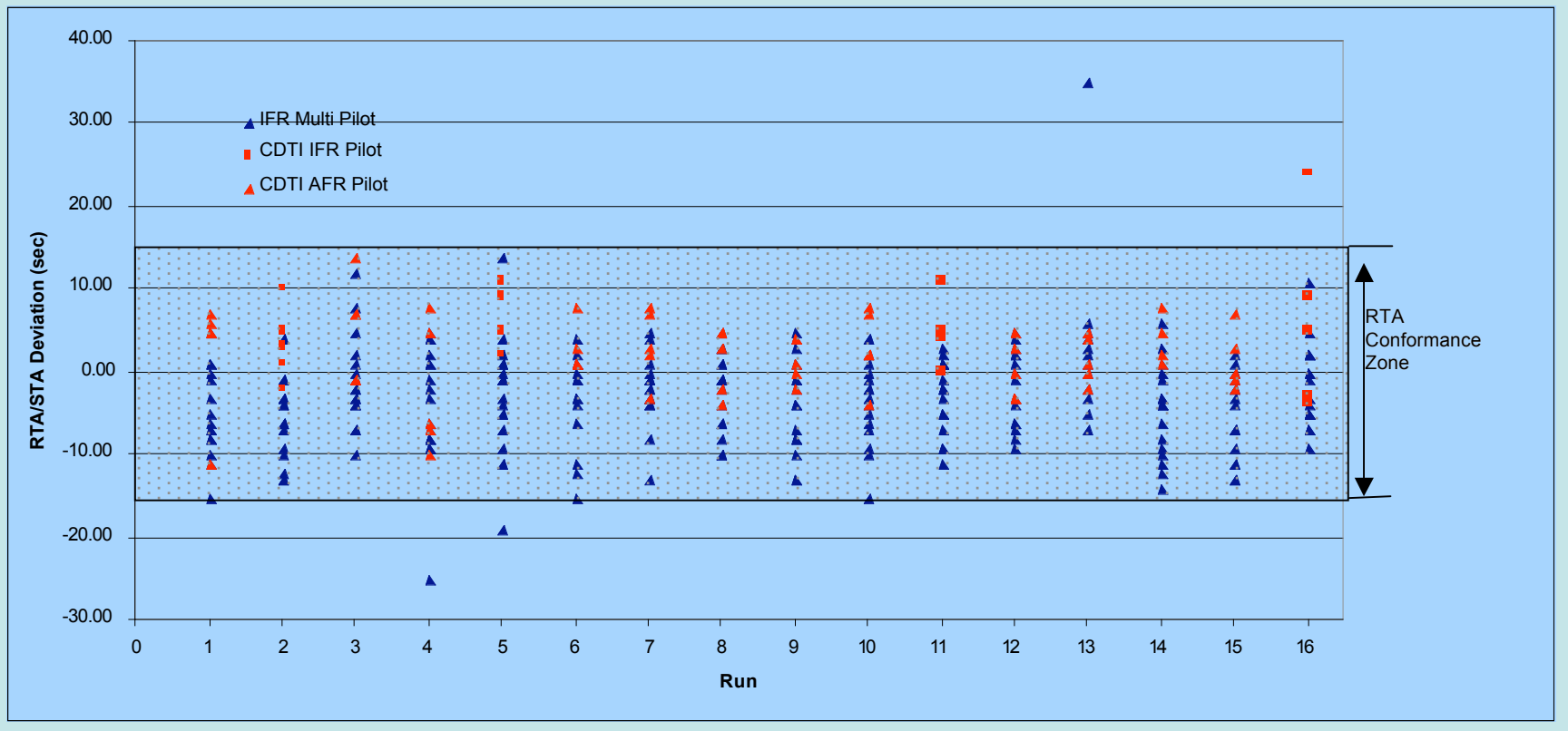
Speeds at BAMBE According to Run



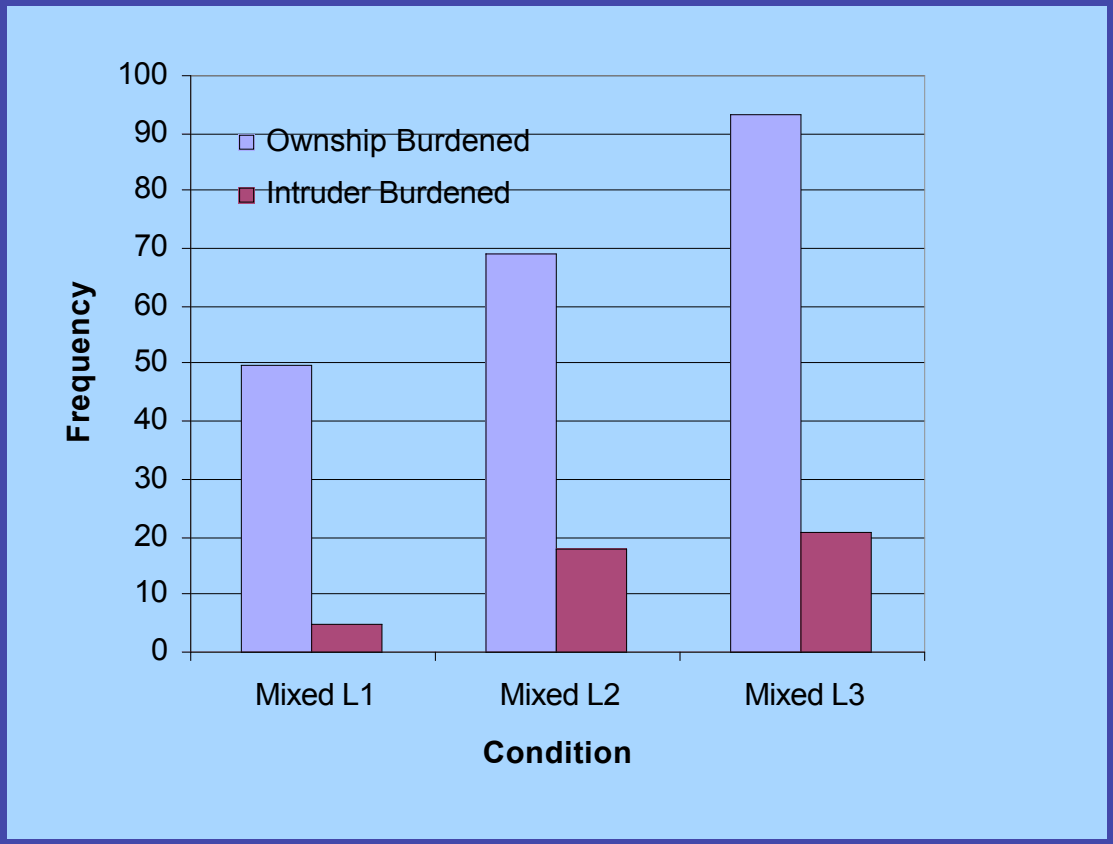
Crossing Altitudes at BAMBE According to Run



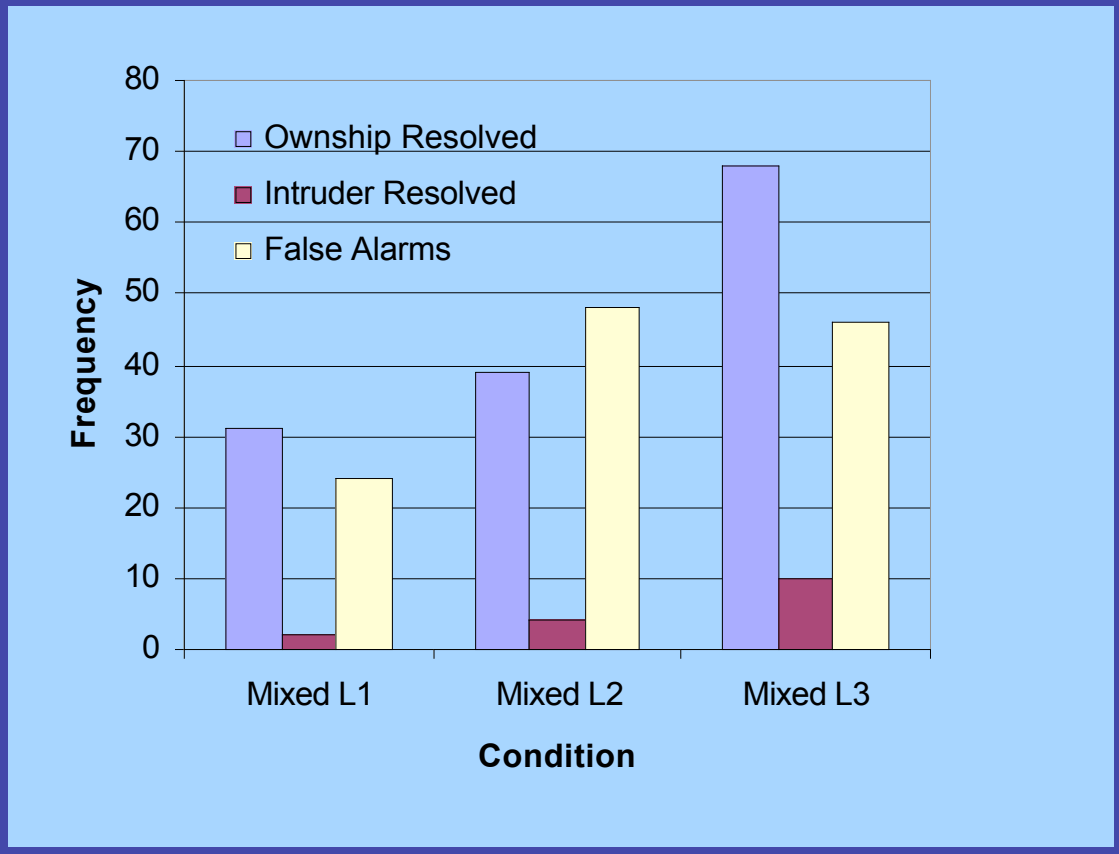
RTA/STA Deviations at the meter fix According to Flight Status and Run



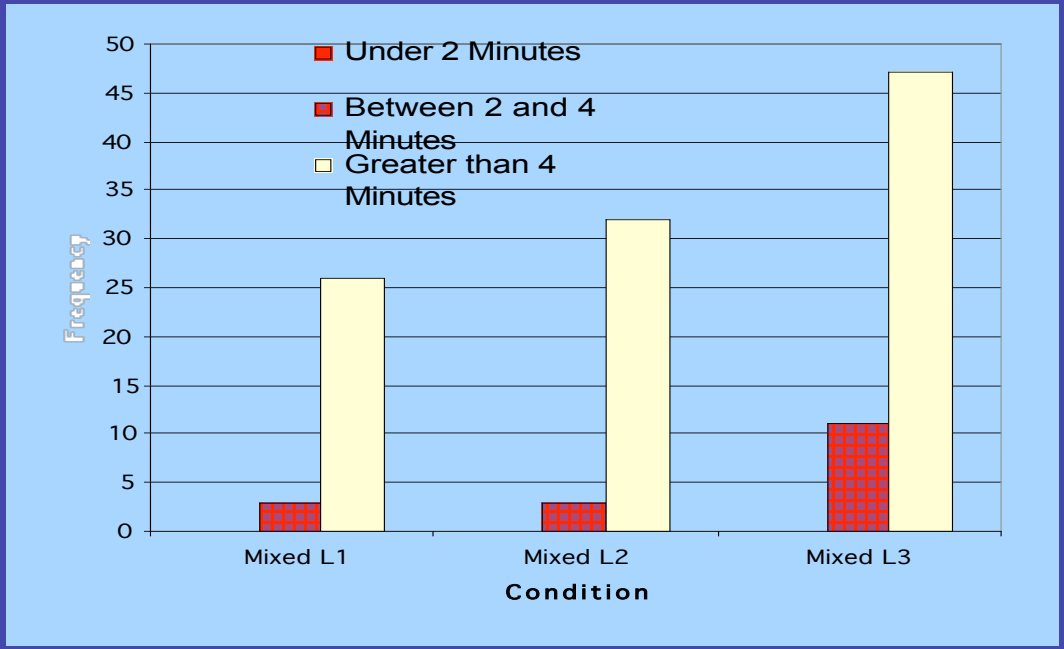
Frequency of Ownship and Intruder Burdened Alerts by Condition



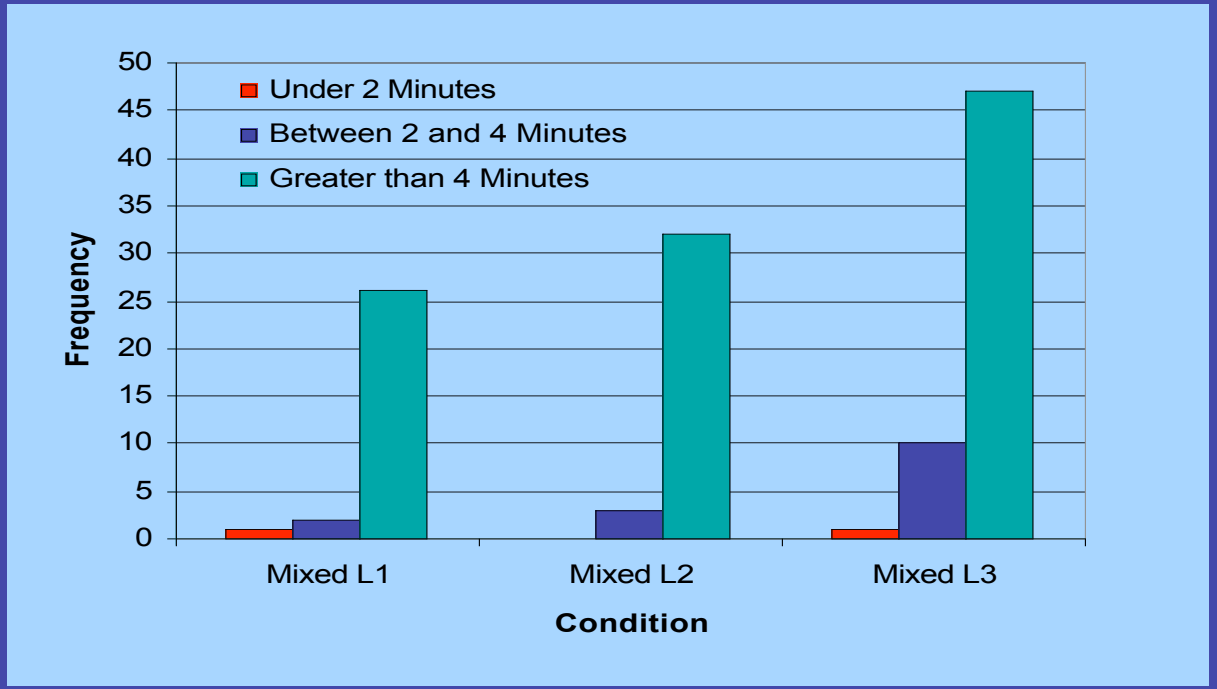
Frequency of Ownship and Intruder Resolutions and False Alerts by Condition



Times Prior to Projected LOS When Conflict First Detected



Time to LOS at Which Conflicts were Resolved



AFR Pilot–Controller Voice Communications

Communication Reason	Mixed-2	Mixed-3	Mixed-4	Total
Initial RTA	-	1	1	2
RTA clarification	2	-	-	2
New RTA	-	-	1	1
Projected conflict at BAMBE	1	2	1	4
Total	3	3	3	9

Pilot Post-Simulation Questionnaire

- After the simulation, the pilots were asked to complete a comprehensive questionnaire.
- The questionnaire was divided into sections, each section containing questions relating to particular aspects of the concept.
- Questions were formatted as open ended or Likert scale responses.

Sample Questions

Both scaled and open-ended questions were used:

14. Overall, did you experience an increase in the number and magnitude of velocity vector changes than you would have in normal (everyday) operations?

1	2	3	4	5
LESS THAN NORMAL		NORMAL		GREATER THAN NORMAL

15. COMMENTS REGARDING TH E S IMULATION ENVIRONMEN T: _____

_____

_____

Concept - Safety

	Absolutely safer	Much safer	Safer	Slightly safer	Same	Slightly safer	Safer	Much safer	Absolutely safer	
AFR Condition	1	1	2	2	2	1				IFR Condition

Pilot Preference Ratings for AFR versus IFR for Overall Safety

The number in each cell indicates the number of pilots that selected a particular response.

Concept - Safety (Con't)

Rank	Overall Safety	Overall Workload	RTA/STA Conformance	Overall SA
1	AFR (0.606)	IFR (0.627)	AFR (0.681)	AFR (0.810)
2	IFR (0.394)	AFR (0.373)	IFR (0.319)	IFR (0.190)

- Pilot preferences were analyzed using the AHP statistical technique (Saaty, 1980), wherein the preference data for each question is transformed into a percentage and averaged for all pilots to produce numerical ranking scores.
- Pilots on average preferred the AFR conditions in terms of overall safety, ease of meeting the RTA/STA, and overall SA. Furthermore, pilots preferred the IFR condition in terms of overall workload.

Concept - Situational Awareness

	Absolutely higher	Much higher	Higher	Slightly higher	Same	Slightly higher	Higher	Much higher	Absolutely higher	
AFR Condition	3	4	1		1					IFR Condition

Pilot Preference Ratings for AFR versus IFR for Overall SA

The number in each cell indicates the number of pilots that selected a particular response.

Ratings for Concept Acceptability

Question	N	Yes	No
Do you feel that AFR operations could potentially introduce performance degradations to the NAS?	10	3	7
Are you comfortable accepting personal responsibility that the basic requirements of separation are met even under periods of high workload?	10	9	1
Are you comfortable resolving conflicts between you and IFR aircraft?	10	10	0
Were you confident performing all collision avoidance tasks?	10	8	2
Are you comfortable accepting total responsibility for maintaining separation?	10	7	3
Are you comfortable ensuring separation without reliance on ATC as a backup?	10	6	4
Are AFR two-person flight crew operations in significantly increased en-route traffic levels feasible?	10	9	1
With sufficient training, would you be comfortable flying with this level of automation?	10	10	0
Do you think an aircraft could take advantage of the flexibility of the concept to maneuver themselves into a better position at the expense of others?	10	9	1

Maintaining Separation

Question	Scale	N	Mean	Std. Dev.
Did traffic density in any way affect your ability to maintain separation?	Completely (5) Not at all (1)	40	1.5	0.96
How difficult was it to maneuver without creating a near-term conflict (less than 4 minutes)?	Easy (5) Very difficult (1)	36	4.7	0.50

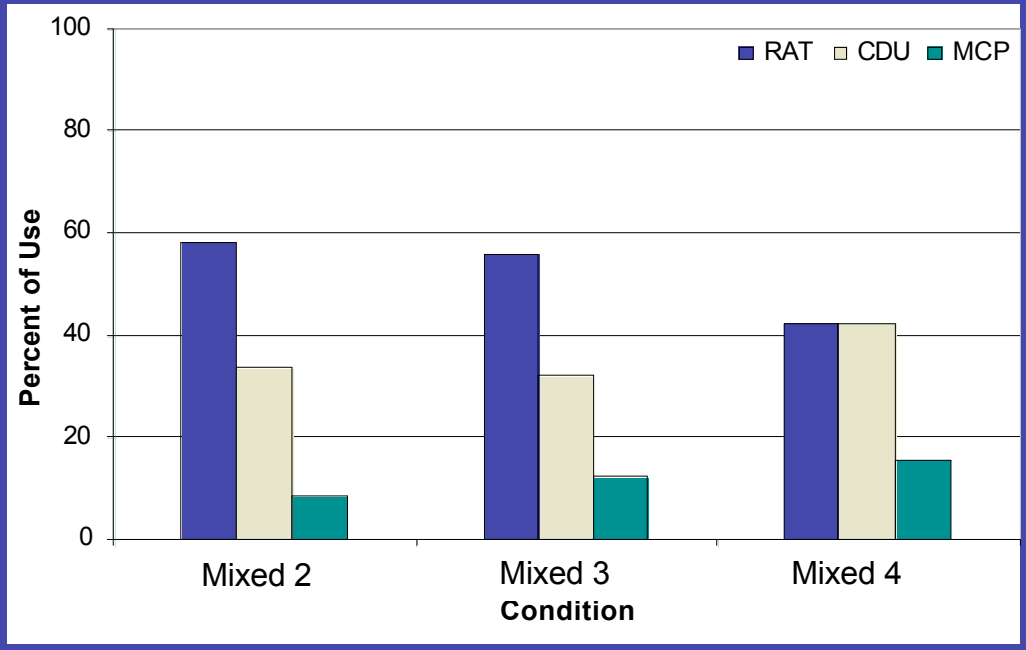
- Pilots responded confidently when asked about their ability to maintain separation while under AFR conditions.
- Traffic density had very little effect on their ability to maintain separation.
- It was generally easy to maneuver without creating new near-term conflicts.
- These responses are consistent with the separation violation data in which no subject-piloted AFR flights were involved in a loss-of-separation (LOS).

Conflict Resolution Strategy

- There was some overlap among the tools and methods because pilots sometimes used multiple means to resolve a single conflict.
- Use of the RAT was fairly consistent across the three conditions it was available.
- As the number of burdened conflicts increased with increased traffic levels, pilots relied more on the CDU and MCP to resolve the conflicts.

Conflict Resolution Strategy (con't.)

Tool Use by Burdened Aircraft to Resolve Conflict by Condition

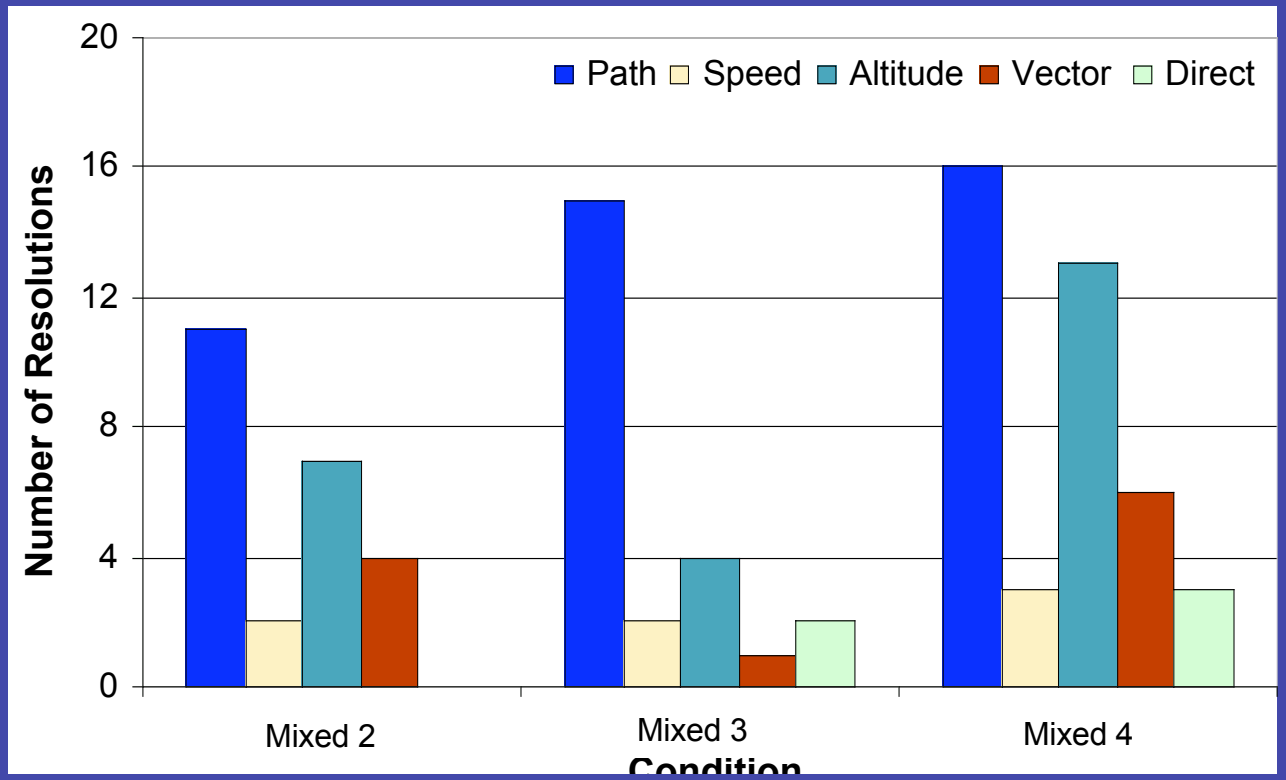


NOTE: A steady increase in CDU and MCP usage with the increase of overflight traffic.

Conflict Resolution Strategy (con't.)

- Pilots tended to favor using the RAT to make lateral path adjustments over other resolution methods with the exception of the highest traffic level (Mixed 4).
- This preference was likely due, to the training the pilots received.
- Pilots most likely favored altitude adjustments during the highest traffic level (Mixed 4) because of the reduced availability of conflict-free alternate routes at lower altitudes.

Conflict Resolution Strategy (con't.)



Method Used by Burdened Aircraft to Resolve Conflict by Condition

Pilot Required Time of Arrival (RTA) Conformance

Question	Scale	N	Mean	Std. Dev.
Did traffic density in any way affect your ability to maintain your RTA?	Completely (5) Not at all (1)	40	1.4	0.93
How acceptable was your RTA assignment?	Acceptable (5) Unacceptable (1)	40	4.9	0.22
How difficult was it to maintain your RTA?	Easy (5) Very difficult (1)	40	4.6	0.64
How effective were you in path-stretching to absorb ATC delays?	Very effective (5) Not effective (1)	36	4.8	0.48

- Pilots reported that traffic density had very little effect on their ability to maintain the assigned RTA.
- Pilots were very effective in path stretching in order to absorb ATC delays and meet their RTA.

CDTI Tools and Interface - Usefulness

- Pilot usability and usefulness ratings of the flight deck tools were overwhelmingly positive.
- Average usefulness ratings ranged from 3.0–5.0 (1 = Not useful, 5 = Very useful).
- Traffic data tag, altitude tail tag, vertical trend arrow, and display range were features that all received high usefulness ratings.

CDTI Tools and Interface - Usability

- The flight path predictor, traffic data tag, altitude tail tag, vertical trend arrow, and display range were some of the features that received very high usability ratings.
- Although all ten pilots felt that they were never provided with too much information, three of 10 pilots found clutter a problem that they were unable to resolve.
- The majority, 8 of 10, responded that they would feel comfortable in resolving all traffic conflicts with the tool-set

Responses to Display and Tool Questions

Question	N	Yes	No
Were you provided with too much information to perform any one of your tasks?	10	0	10
Was the toolset provided sufficient to perform arrival tasks?	10	10	0
With the toolset provided, were you able to respond to traffic conflict situations well before the conflicting aircraft posed a hazard to safety of flight?	10	10	0
Would you feel comfortable with the CDTI toolset provided to resolve all traffic conflicts?	10	8	2
Would you feel comfortable with the tool-set provided to self-route through dynamic en-route weather hazards accurately displayed on the CDTI?	10	7	3

CDTI 2D/3D Display Modes

- The 3D-view feature was rated favorably for usability (*M* = 4.2) and usefulness (*M* = 4.1).
- All of the pilots reported viewing the CDTI in both 2D and 3D modes for at least some portion of each simulation day.
- The Pilots estimated they viewed the CDTI in 3D 36 percent of the time.

Pilot Workload

- A subjective workload assessment form was administrated, post-run, to the pilots using the Modified Cooper Harper (MCH).
- System software collected task load measures that include air/ground communications data, the number and type of clearances sent by a controller, and the maneuvers made by an AFR aircraft.

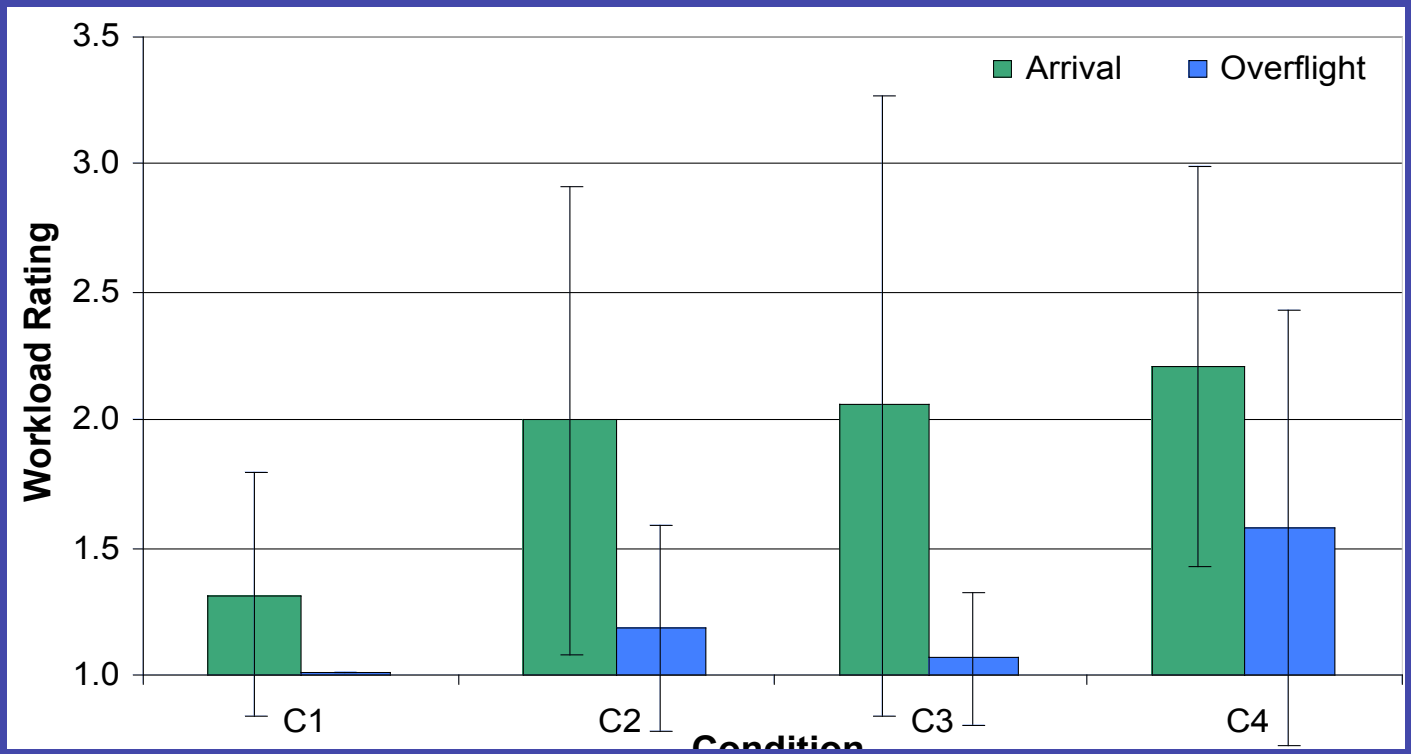
MCH Workload Results

- The MCH allows for ratings between **1** (*Very easy/workload insignificant*) and **10** (*Impossible/task abandoned, unable to apply sufficient effort*).
- Pilot responses across all runs ranged from 1 to 6.
- Approximately 98 percent of responses ranged from 1 to 3.
- In order to receive a rating between 1 and 3, it must be possible to complete the task, and workload must be perceived as tolerable and satisfactory.
- Ratings from 4 to 6 suggest that task workload is high but not high enough to impact performance on the primary task.

MCH Workload Results (con't)

- Pilots responded unanimously with the lowest possible workload rating (1) for the managed overflight runs (all managed).
- Results indicate that pilots felt that workload increased when flying under autonomous operations as opposed to managed, but workload remained acceptably low.

Average MCH Ratings by Condition and Type of Flight



These results suggest that neither arrival nor overflight pilots felt that workload appreciably increased as traffic increased (C2 - C4).

Pilot Suggestions

- Support RTA conformance by providing the ability to adjust airspeed when path stretching to meet an RTA.
- Provide the ability to view a full flight plan while in a reduced vertical-scale setting in 3D mode.
- Provide the ability to examine distant conflicts in a high-resolution scale (i.e., show targets at 80 nm in a 10 nm scale).

General Conclusion

The Ames AFR pilots had very little difficulty in performing their assigned tasks, and found the concept both acceptable and desirable. The increase in traffic had little or no negative impact on their performance or opinion. Thus, from the Ames airside perspective, both the feasibility and scalability hypotheses were upheld.

Ames Airside Group Photo